

NIST NCSTAR 1

Federal Building and Fire Safety Investigation
of the World Trade Center Disaster

Final Report on the **Collapse of the World Trade Center Towers**

NIST

**National Institute of
Standards and Technology**

Technology Administration
U.S. Department of Commerce

NIST NCSTAR 1

Federal Building and Fire Safety Investigation
of the World Trade Center Disaster

Final Report on the **Collapse of the World Trade Center Towers**

September 2005



U.S. Department of Commerce
Carlos M. Gutierrez, Secretary

Technology Administration
Michelle O'Neill, Acting Under Secretary for Technology

National Institute of Standards and Technology
William Jeffrey, Director

Disclaimer No. 1

Certain commercial entities, equipment, products, or materials are identified in this document in order to describe a procedure or concept adequately or to trace the history of the procedures and practices used. Such identification is not intended to imply recommendation, endorsement, or implication that the entities, products, materials, or equipment are necessarily the best available for the purpose. Nor does such identification imply a finding of fault or negligence by the National Institute of Standards and Technology.

Disclaimer No. 2

The policy of NIST is to use the International System of Units (metric units) in all publications. In this document, however, units are presented in metric units or the inch-pound system, whichever is prevalent in the discipline.

Disclaimer No. 3

Pursuant to section 7 of the National Construction Safety Team Act, the NIST Director has determined that certain evidence received by NIST in the course of this investigation is "voluntarily provided safety-related information" that is "not directly related to the building failure being investigated" and that "disclosure of that information would inhibit the voluntary provision of that type of information" (15 USC 7306c).

In addition, a substantial portion of the evidence collected by NIST in the course of the investigation has been provided to NIST under nondisclosure agreements.

Disclaimer No. 4

NIST takes no position as to whether the design or construction of a WTC building was compliant with any code since, due to the destruction of the WTC buildings, NIST could not verify the actual (or as-built) construction, the properties and condition of the materials used, or changes to the original construction made over the life of the buildings. In addition, NIST could not verify the interpretations of codes used by applicable authorities in determining compliance when implementing building codes. Where an investigation report states whether a system was designed or installed as required by a code *provision*, NIST has documentary or anecdotal evidence indicating whether the requirement was met, or NIST has independently conducted tests or analyses indicating whether the requirement was met.

Use in Legal Proceedings

No part of any report resulting from a NIST investigation into a structural failure or from an investigation under the National Construction Safety Team Act may be used in any suit or action for damages arising out of any matter mentioned in such report (15 USC 281a; as amended by P.L. 107-231).

**National Institute of Standards and Technology National Construction Safety Team Act Report 1
Natl. Inst. Stand. Technol. Natl. Constr. Sfty. Tm. Act Rpt. 1, 298 pages (September 2005)
CODEN: NSPUE2**

U.S. GOVERNMENT PRINTING OFFICE
WASHINGTON: 2005

For sale by the Superintendent of Documents, U.S. Government Printing Office
Internet: bookstore.gpo.gov — Phone: (202) 512-1800 — Fax: (202) 512-2250
Mail: Stop SSOP, Washington, DC 20402-0001

NATIONAL CONSTRUCTION SAFETY TEAM FOR THE FEDERAL BUILDING AND FIRE SAFETY INVESTIGATION OF THE WORLD TRADE CENTER DISASTER

S. Shyam Sunder, Sc.D. (NIST)	Lead Investigator
Richard G. Gann, Ph.D. (NIST)	Final Report Editor; Project Leader, Project 5: Reconstruction of Thermal and Tenability Environment
William L. Grosshandler, Ph.D. (NIST)	Associate Lead Investigator; Project Leader, Project 4: Investigation of Active Fire Protection Systems
H.S. Lew, Ph.D., P.E. (NIST)	Co-Project Leader, Project 1: Analysis of Building and Fire Codes and Practices
Richard W. Bukowski, P.E. (NIST)	Co-Project Leader, Project 1: Analysis of Building and Fire Codes and Practices
Fahim Sadek, Ph.D. (NIST)	Project Leader, Project 2: Baseline Structural Performance and Aircraft Impact Damage Analysis
Frank W. Gayle, Ph.D. (NIST)	Project Leader, Project 3: Mechanical and Metallurgical Analysis of Structural Steel
John L. Gross, Ph.D., P.E. (NIST)	Co-Project Leader, Project 6: Structural Fire Response and Collapse Analysis
Therese P. McAllister, Ph.D., P.E. (NIST)	Co-Project Leader, Project 6: Structural Fire Response and Collapse Analysis
Jason D. Averill (NIST)	Project Leader, Project 7: Occupant Behavior, Egress, and Emergency Communications
J. Randall Lawson (NIST)	Project Leader, Project 8: Fire Service Technologies and Guidelines
Harold E. Nelson, P.E.	Fire Protection Engineering Expert
Stephen A. Cauffman (NIST)	Program Manager

This page intentionally left blank.

CONTRIBUTORS TO THE INVESTIGATION

NIST TECHNICAL STAFF

Mohsen Altafi	Jeffrey Fong	Max Peltz
Robert Anleitner	Glenn Forney	Lisa Petersen
Elisa Baker	William Fritz	Rochelle Plummer
Stephen Banovic	Anthony Hamins	Kuldeep Prasad
Howard Baum	Edward Hnetkovsky	Natalia Ramirez
Carlos Beauchamp	Erik Johnsson	Ronald Rehm
Dale Bentz	Dave Kelley	Paul Reneke
Charles Bouldin	Mark Kile	Michael Riley
Paul Brand	Erica Kuligowski	Lonn Rodine
Lori Brassell	Jack Lee	Schuyler Ruitberg
Kathy Butler	William Luecke	Jose Sanchez
Nicholas Carino	Alexander Maranghides	Raymond Santoyo
Sandy Clagett	David McColskey	Steven Sekellick
Ishmael Conteh	Chris McCowan	Michael Selepak
Matthew Covin	Jay McElroy	Thomas Siewert
Frank Davis	Kevin McGrattan	Emil Simiu
David Dayan	Roy McLane	Monica Starnes
Laurean DeLauter	George Mulholland	David Stroup
Jonathan Demarest	Lakeshia Murray	Laura Sugden
Stuart Dols	Kathy Notarianni	Robert Vettori
Michelle Donnelly	Joshua Novosel	John Widmann
Dat Duthinh	Long Phan	Brendan Williams
David Evans	William Pitts	Maureen Williams
Richard Fields	Thomas Ohlemiller	Jiann Yang
James Filliben	Victor Ontiveros	Robert Zarr
Tim Foecke	Richard Peacock	

NIST EXPERTS AND CONSULTANTS

Vincent Dunn
 Steven Hill
 John Hodgens
 Kevin Malley
 Valentine Junker

DEPARTMENT OF COMMERCE AND NIST INSTITUTIONAL SUPPORT

Michele Abadia-Dalmau	James Hill	Karen Perry
Kellie Beall	Verna Hines	Sharon Rinehart
Arden Bement, Jr.	Kathleen Kilmer	Michael Rubin
Audra Bingaman	Kevin Kimball	Rosamond Rutledge-Burns
Sharon Bisco	Thomas Klausing	John Sanderson
Phyllis Boyd	Donna Kline	Hratch Semerjian
Marie Bravo	Fred Kopatich	Sharon Shaffer
Craig Burkhardt	Kenneth Lechter	Elizabeth Simon
Paul Cataldo	Melissa Lieberman	Jack Snell
Virginia Covahey	Darren Lowe	Michael Szwed
Deborah Cramer	Mark Madsen	Kelly Talbott
Gail Crum	Ronald Meininger	Anita Tolliver
Jane Dana	Romena Moy	Joyce Waters
Sherri Diaz	Michael Newman	Teresa Vicente
Sandra Febach	Gail Porter	Dawn Williams
Susan Ford	Thomas O'Brian	
James Fowler	Nualla O'Connor-Kelly	
Matthew Heyman	Norman Osinski	

NIST CONTRACTORS

Applied Research Associates, Inc.

Steven Kirkpatrick*	Marsh Hardy	Claudia Navarro
Robert T. Bocchieri	Samuel Holmes	Brian D. Peterson
Robert W. Cilke	Robert A. MacNeill	Justin Y-T. Wu

Baseline, Inc.

Martin Klain

Computer Aided Engineering Associates, Inc.

Peter Barrett*	Daniel Fridline
Michael Bak	James J. Kosloski

DataSource, Inc.

John Wivaag

GeoStats, Inc.

Marcello Oliveira

Gilsanz Murray Steficek LLP

Ramon Gilsanz

Hughes Associates, Inc.

Ed Budnick*

Mike Ferreira*

Mark Hopkins

Matt Hulcher

Alwin Kelly

Chris Mealy

John Schoenrock

Steven Strege

Karen Dawn Tooren

Independent Contractors

Ajmal Abbasi

Eduardo Kausel

David Parks

David Sharp

Daniele Veneziano

Josef Van Dyck

Kaspar Willam

Isolatek International, Inc.

Paulette Kaminski

John Jay College

Norman Groner

Leslie E. Robertson Associates, R.L.L.P.

William J. Faschan*

Richard B. Garlock*

William C. Howell

Raymond C. Lai

National Fire Protection Association

Rita Fahey*

Norma Candeloro

Joseph Molis

National Research Council, Canada

Gyulene Proulx*

Amber Walker

NuStats, Inc.

Johanna Zmud*

Carlos Arce

Heather Contrino

Christopher Frye

Nancy McGuckin

Sandra Rodriguez

Della Santos

Robert Santos

Rolf Jensen & Associates, Inc.

Ray Grill*

Ed Armm

Tom Brown

Duane Johnson

Bob Keough

Joseph Razz

Rosenwasser/Grossman Consulting Engineers, P.C.

Jacob Grossman*

Craig Leech

Arthur Seigel

Science Applications International Corporation

John Eichner*

Cheri Sawyer*

Lori Ackman

Marina Bogatine

Sydel Cavanaugh

Kathleen Clark

Pamela Curry

John DiMarzio

Heather Duvall

Mark Huffman

Charlotte Johnson

Michael Kalmar

Mark Madara

Walter Soverow

Paul Updike

Yvonne Zagadou

Simpson Gumpertz & Heger Inc.

Mehdi Zarghamee*

Glenn Bell

Said Bolourchi

Daniel W. Eggers

Ömer O. Erbay

Ron Hamburger

Frank Kan

Yasuo Kitane

Atis Liepins

Michael Mudlock

Wassim I. Naguib

Rasko P. Ojdrovic

Andrew T. Sarawit

Pedro Sifre

S. K. Ghosh Associates, Inc.

S. K. Ghosh*

Analdo Derecho

Dave Fanella

Xumei Liang

Skidmore, Owings & Merrill, LLP

Bill Baker

Bob Sinn

John Zils

Teng & Associates, Inc.

Shankar Nair

Underwriters Laboratories, Inc.

Fred Hervey*

Joseph Treadway*

Mark Izydorek

Aldo Jimenez

William Joy

John Mammoser

University at Buffalo, The State University of New York

Andrew Whitaker*

Andrei Reinhorn

Joshua Repp

**University of Chicago Survey
Lab**

Virginia Bartot

Martha van Haitsma

University of Colorado

Dennis Mileti

University of Michigan

Jamie Abelson

Wiss, Janney, Elstner Associates, Inc.

Ray Tide*

Jim Hauck

Conrad Paulson

COOPERATING ORGANIZATIONS**American Airlines**

Desmond Barry

Morgan Heyer

The Boeing Company

Marlene Nelson

**Blanford Land Development
Corporation**

Lisa Lickman

Ron Lickman

John Sandy

Carr Futures, Inc.

David Mangold

**City of New York Fire
Department**

Alexandra Fisher

Allen S. Hay

**Federal Bureau of
Investigation**

Kenneth Marr

Hugo Neu Schnitzer East

Robert Kelman

Steve Shinn

Frank Manzo

Laclede Steel

David McGee

**Marsh & McLennan
Companies**

Thomas Gress

Michael Lyons

Metal Management Northeast, Inc.

Michael Henderson

Alan Ratner

John Silva

National Commission on Terrorist Attacks Upon the United States

Madeline Blot

Sam M. W. Casperson

George L. Delgrosso

Daniel Marcus

James Miller

Catherine S. Taylor

Contributors to the Investigation

New York City Law Department

Lawrence S. Kahn

Jay L. Cohen

Gary Shaffer

Rachel Relkin

Joanna Weiss

George C. D. Duke

Katherine Winningham

Jessie Levine

New York City Police Department

Michael F. Healey

The Port Authority of New York and New Jersey

James Begley

Saroj Bhol

Gerry Gaeta

Jeffrey Gertier

Frank Lombardi

Alan Reiss

Nancy Seliga

Siemens

Steven Shamash

John Farrington

Robert Salamone

Silverstein Properties

**Simpson, Thacher & Bartlett
LLP**

Jamie Gamble

**Structural Engineers
Association of New York**

Ed DiPaolo

**Wachtell, Lipton, Rosen &
Katz**

Marc Wolinsky

Andrew Cheung

United Air Lines

John Midgett

Norvis Huevo

Williams & Connolly LLP

Philip Sechler

*Principal Investigator/Key Contact

DEDICATION

On the morning of September 11, 2001, Americans and people around the world were shocked by the destruction of the World Trade Center (WTC) in New York City and the devastation of the Pentagon near Washington, D.C., after large aircraft were flown into the buildings, and the crash of an aircraft in a Pennsylvania field that averted further tragedy. Four years later, the world has been changed irrevocably by those terrorist attacks. For some, the absence of people close to them is a constant reminder of the unpredictability of life and death. For millions of others, the continuing threats of further terrorist attacks affect how we go about our daily lives and the attention we must give to homeland security and emergency preparedness.

Within the construction, building, and public safety communities, there arose a question pressing to be answered: How can we reduce our vulnerability to such attacks, and how can we increase our preparedness and safety while still ensuring the functionality of the places in which we work and live?

This Investigation has, to the best extent possible, reconstructed the response of the WTC towers and the people on site to the consequence of the aircraft impacts. It provides improved understanding to the professional communities and building occupants whose action is needed and to those most deeply affected by the events of that morning. In this spirit, this report is dedicated to those lost in the disaster, to those who have borne the burden to date, and to those who will carry it forward to improve the safety of buildings.

This page intentionally left blank.

ABSTRACT

This is the final report on the National Institute of Standards and Technology (NIST) investigation of the collapse of the World Trade Center (WTC) towers, conducted under the National Construction Safety Team Act. This report describes how the aircraft impacts and subsequent fires led to the collapse of the towers after terrorists flew jet fuel laden commercial airliners into the buildings; whether the fatalities were low or high, including an evaluation of the building evacuation and emergency response procedures; what procedures and practices were used in the design, construction, operation, and maintenance of the towers; and areas in current building and fire codes, standards, and practices that warrant revision. Extensive details are found in the 42 companion reports. The final report on the collapse of WTC 7 will appear in a separate report.

Also in this report is a description of how NIST reached its conclusions. NIST complemented in-house expertise with private sector technical experts; accumulated copious documents, photographs, and videos of the disaster; established baseline performance of the WTC towers; performed computer simulations of the behavior of each tower on September 11, 2001; combined the knowledge gained into a probable collapse sequence for each tower; conducted nearly 1,200 first-person interviews of building occupants and emergency responders; and analyzed the evacuation and emergency response operations in the two high-rise buildings.

The report concludes with a list of 30 recommendations for action in the areas of increased structural integrity, enhanced fire endurance of structures, new methods for fire resistant design of structures, enhanced active fire protection, improved building evacuation, improved emergency response, improved procedures and practices, and education and training.

Keywords: Aircraft impact, building evacuation, emergency response, fire safety, human behavior, structural collapse, tall buildings, wind engineering, World Trade Center.

This page intentionally left blank.

TABLE OF CONTENTS

National Construction Safety Team for the Federal Building and Fire Safety Investigation of the World Trade Center Disaster	iii
Contributors to the Investigation.....	v
Dedication	xi
Abstract.....	xiii
List of Figures.....	xxi
List of Tables	xxv
List of Acronyms and Abbreviations	xxvii
Preface	xxix
Executive Summary	xxxv
 Part I: September 11, 2001	 1
 Chapter 1	
New York City's World Trade Center	1
1.1 The Origination.....	1
1.2 The World Trade Center Complex	2
1.2.1 The Site.....	2
1.2.2 The Towers.....	5
 Chapter 2	
The Account of World Trade Center 1	19
2.1 8:46:30 a.m. EDT.....	19
2.2 The Aircraft.....	20
2.3 The Immediate Damage.....	20
2.4 The Jet Fuel.....	24
2.5 8:47 a.m. to 9:02 a.m. EDT.....	24
2.6 9:02:59 a.m. EDT.....	27
2.7 9:03 a.m. to 9:57 a.m. EDT.....	27
2.8 9:58:59 a.m. EDT.....	32
2.9 9:59 a.m. to 10:28 a.m. EDT.....	32
2.10 The Outcome.....	34

Chapter 3

The Account of World Trade Center 2	37
3.1 8:46:30 a.m. EDT.....	37
3.2 9:02:59 a.m. EDT.....	38
3.3 The Immediate Damage	38
3.4 The Jet Fuel.....	42
3.5 9:03 a.m. to 9:36 a.m. EDT.....	42
3.6 9:36 a.m. to 9:58 a.m. EDT.....	44
3.7 The Outcome.....	45

Chapter 4

The Toll	47
-----------------------	-----------

Part II: Reconstructing the Disaster	49
---	-----------

Chapter 5

The Design and Construction of the Towers	51
5.1 Building and Fire Codes	51
5.2 The Codes and the Towers.....	52
5.2.1 The New York City Building Code.....	52
5.2.2 Pertinent Construction Provisions	53
5.2.3 Tenant Alteration Process.....	54
5.3 Building Design	55
5.3.1 Loads	55
5.3.2 Aircraft Impact	55
5.3.3 Construction Classification and Fire Resistance Rating.....	55
5.3.4 Compartmentation	56
5.3.5 Egress Provisions	57
5.3.6 Active Fire Protection	61
5.4 Building Innovations.....	64
5.4.1 The Need for Innovations.....	64
5.4.2 Framed Tube System	64
5.4.3 Deep Spandrel Plates.....	64
5.4.4 Uniform External Column Geometry	65
5.4.5 Wind Tunnel Test Data to Establish Wind Loads	65
5.4.6 Viscoelastic Dampers	65

5.4.7 Long-Span Composite Floor Assemblies	66
5.4.8 Vertical Shaft Wall Panels.....	66
5.5 Structural Steels	67
5.5.1 Types and Sources.....	67
5.5.2 Properties.....	67
5.6 Fire Protection of Structural Steel.....	69
5.6.1 Thermal Insulation	69
5.6.2 Use of Insulation in the WTC Towers.....	69
5.7 Concrete	75
5.8 The Tenant Spaces	75
5.8.1 General	75
5.8.2 Walls.....	76
5.8.3 Flooring	76
5.8.4 Ceilings.....	76
5.8.5 Furnishings.....	76

Chapter 6

Reconstruction of the Collapses	81
6.1 Approach.....	81
6.2 Development of the Disaster Timeline	82
6.3 Learning from the Visual Images	84
6.4 Learning from the Recovered Steel	86
6.4.1 Collection of Recovered Steel	86
6.4.2 Mechanical and Physical Properties	88
6.4.3 Damage Analysis.....	89
6.5 Information Gained from Other WTC Fires	91
6.6 The Building Structural Models.....	92
6.6.1 Computer Simulation Software	92
6.6.2 The Reference Models.....	92
6.6.3 Building Structural Models for Aircraft Impact Analysis	94
6.6.4 Building Structural Models for Structural Response to Impact Damage and Fire and Collapse Initiation Analysis	97
6.7 The Aircraft Structural Model	105
6.8 Aircraft Impact Modeling	107
6.8.1 Component Level Analyses.....	107
6.8.2 Subassembly Impact Analyses	108

6.8.3 Aircraft Impact Conditions.....	108
6.8.4 Global Impact Analysis	109
6.9 Aircraft Impact Damage Estimates	112
6.9.1 Structural and Contents Damage	112
6.9.2 Validity of Impact Simulations	116
6.9.3 Damage to Thermal Insulation	119
6.9.4 Damage to Ceiling System	120
6.9.5 Damage to Interior Walls and Furnishings.....	120
6.10 Thermal Environment Modeling.....	121
6.10.1 Need for Simulation	121
6.10.2 Modeling Approach.....	121
6.10.3 The Four Cases.....	126
6.10.4 Characterization of the Fires	127
6.10.5 Global Heat Release Rates	130
6.11 Data Transfer	131
6.12 Thermal Mapping	131
6.12.1 Approach	131
6.12.2 The Fire-Structure Interface	131
6.12.3 Thermal Insulation Properties	132
6.12.4 FSI Uncertainty Assessment.....	133
6.12.5 The Four Cases.....	138
6.12.6 Characterization of the Thermal Profiles.....	141
6.13 Measurement of the Fire Resistance of the Floor System	141
6.14 Collapse Analysis of the Towers	143
6.14.1 Approach to Determining the Probable Collapse Sequences	143
6.14.2 Results of Global Analysis of WTC 1	144
6.14.3 Results of Global Analysis of WTC 2.....	145
6.14.4 Events Following Collapse Initiation	146
6.14.5 Structural Response of the WTC Towers to Fire without Impact or Thermal Insulation Damage.....	146
6.14.6 Probable WTC 1 Collapse Sequence.....	150
6.14.7 Probable WTC 2 Collapse Sequence.....	151
6.14.8 Accuracy of the Probable Collapse Sequences.....	152
6.14.9 Factors that Affected Building Performance on September 11, 2001	154

Chapter 7**Reconstruction of Human Activity 155**

7.1 Building Occupants.....	155
7.1.1 Background	155
7.1.2 The Building Egress System	155
7.1.3 The Evacuation—Data Sources.....	157
7.1.4 Occupant Demographics	158
7.1.5 Evacuation of WTC 1.....	158
7.1.6 Evacuation of WTC 2.....	160
7.2 Emergency Responders.....	163
7.2.1 Data Gathered.....	163
7.2.2 Operation Changes following the WTC 1 Bombing on February 26, 1993	164
7.2.3 Responder Organization	166
7.2.4 Responder Access.....	169
7.2.5 Communications.....	170
7.2.6 The Overall Response	172
7.3 Factors That Contributed to Enhanced Life Safety.....	172
7.3.1 Aggregate Factors.....	172
7.3.2 Individual Factors.....	172

Part III: The Outcome of the Investigation 173**Chapter 8****Principal Findings 175**

8.1 Introduction.....	175
8.2 Summary	175
8.3 Findings on the Mechanisms of Building Collapse	179
8.3.1 Summary of Probable Collapse Sequences	179
8.3.2 Structural Steels.....	180
8.3.3 Aircraft Impact Damage Analysis	182
8.3.4 Reconstruction of the Fires.....	183
8.3.5 Structural Response and Collapse Analysis	185
8.4 Findings on Factors Affecting Life Safety.....	186
8.4.1 Active Fire Protection	186
8.4.2 Evacuation	188
8.4.3 Emergency Response	191

8.5 Findings on Operational Codes, Standards, and Practices	194
8.5.1 General	194
8.5.2 Structural Safety	195
8.5.3 Fire Safety	196
8.6 Future Factors That Could Have Improved Life Safety	199
8.6.1 Building Performance Factors	200
8.6.2 Human Performance Factors	200
 Chapter 9	
Recommendations	201
9.1 Building Regulations	201
9.2 NIST's Recommendations for Improving the Safety of Buildings, Occupants, and Emergency Responders	202
9.2.1 Group 1. Increased Structural Integrity	205
9.2.2 Group 2. Enhanced Fire Endurance of Structures	208
9.2.3 Group 3. New Methods for Fire Resistant Design of Structures	211
9.2.4 Group 4. Improved Active Fire Protection	213
9.2.5 Group 5. Improved Building Evacuation	214
9.2.6 Group 6. Improved Emergency Response	218
9.2.7 Group 7. Improved Procedures and Practices	220
9.2.8 Group 8. Education and Training	222
9.3 Next Steps	223
 Appendix A	
National Construction Safety Team Act	
 Appendix B	
World Trade Center Investigation Publications	
 Appendix C	
Subject Index of Supporting Investigation Reports	

LIST OF FIGURES

Figure P-1.	The eight projects in the federal building and fire safety investigation of the WTC disaster.	xxxi
Figure 1-1.	The World Trade Center in Lower Manhattan.....	3
Figure 1-2.	Lower Manhattan and the World Trade Center towers.....	4
Figure 1-3.	Tower floor plans with column numbers.	7
Figure 1-4.	Perimeter column/spandrel assembly and floor structure.	8
Figure 1-5.	Plan of the 96 th floor of WTC 1 showing the core and tenant spaces.	9
Figure 1-6.	Schematic of composite floor truss system.....	10
Figure 1-7.	Schematic of a hat truss.	11
Figure 1-8.	Photograph of insulated WTC trusses.....	12
Figure 1-9.	Schematic of the three-tier elevator system.	14
Figure 1-10.	Orientation of the three stairwells.....	16
Figure 1-11.	Views of typical WTC office floors.....	17
Figure 1-12.	A WTC trading floor.....	17
Figure 2-1.	Simulated impact of American Airlines Flight 11 with WTC 1.....	19
Figure 2-2.	Aircraft entry hole on the north side of WTC 1, photographed 30 s after impact.	21
Figure 2-3.	South face damage of WTC 1 with key aircraft component locations marked.....	22
Figure 2-4.	Simulation of cumulative aircraft impact damage to floors 93 through 98 in WTC 1.....	23
Figure 2-5.	Representation of exterior views of the fires on the four faces of WTC 1 from 8:47 a.m. to about 9:02 a.m.....	25
Figure 2-6.	Firefighters on the scene at about 9:07 a.m.....	27
Figure 2-7.	Representation of exterior views of the fires on the four faces of WTC 1 from about 9:38 a.m. to 9:58 a.m.	28
Figure 2-8.	Steel surface temperatures on the bottom chords of fire-exposed trusses, uninsulated and insulated with ¾ in. of BLAZE-SHIELD DC/F.....	29
Figure 2-9.	Temperature dependence of yield strength of structural steel as a fraction of the value at room temperature.	30
Figure 2-10.	Simulated temperatures of two adjacent trusses (left) and two adjacent perimeter columns (right) exposed to the fires in WTC 1.....	30
Figure 2-11.	Temperature contours (°C) on the top and bottom faces of the concrete slab (96 th floor, WTC 1) at 100 min after impact. A portion of the concrete slab on the north face (top) was damaged by the impact of the aircraft.	31

List of Figures

Figure 2–12.	South face of WTC 1 at 10:23 a.m., showing inward buckling (in inches) of perimeter columns.....	33
Figure 3–1.	Imminent impact of United Airlines Flight 175 with WTC 2.....	38
Figure 3–2.	South face damage of WTC 2 with key aircraft component locations marked.....	39
Figure 3–3.	Simulation of aircraft impact damage to the 78 th through 83 rd floors in WTC 2.	40
Figure 3–4.	Representation of exterior views of the fires on the four faces of WTC 2 at about 9:20 a.m.....	43
Figure 3–5.	Photograph of WTC 2 tilting to the southeast at the onset of collapse.	45
Figure 4–1.	The WTC site on September 17, 2001.....	47
Figure 5–1.	Fire Command Desk in WTC 1, as seen from a mezzanine elevator, looking west.	61
Figure 5–2.	Schematic of sprinkler and standpipe systems.....	63
Figure 5–3.	Diagram of floor truss showing viscoelastic damper.....	66
Figure 5–4.	Ratio of measured yield strength (F_y) to specified minimum yield strength for steels used in WTC perimeter columns.	69
Figure 5–5.	Irregularity of coating thickness and gaps in coverage on SFRM-coated bridging trusses.....	71
Figure 5–6.	Thermal insulation for perimeter columns.....	72
Figure 5–7.	Temperature-dependent concrete properties.	75
Figure 5–8.	A WTC workstation.	76
Figure 6–1.	9:26:20 a.m. showing the east face of WTC 2.	85
Figure 6–2.	Close-up of section of Figure 6–1.....	86
Figure 6–3.	Examples of a WTC 1 core column (left) and truss material (right).....	88
Figure 6–4.	WTC 1 exterior panel hit by the fuselage of the aircraft.....	88
Figure 6–5.	WTC 1 exterior panel hit by the nose of the aircraft.....	89
Figure 6–6.	Structural model of the 96 th floor of WTC 1.....	95
Figure 6–7.	Model of the 96 th floor of WTC 1, including interior contents and partitions.	95
Figure 6–8.	Multi-floor global model of WTC 1, viewed from the north.	96
Figure 6–9.	Multi-floor global model of WTC 2, viewed from the south.....	96
Figure 6–10.	Finite element model of an exterior truss seat.	98
Figure 6–11.	Vertical displacement at 700 °C.....	98
Figure 6–12.	ANSYS model of 96 th floor of WTC 1.	99
Figure 6–13.	Finite element model of the Boeing 767-200ER.....	105

Figure 6-14. Pratt & Whitney PW4000 turbofan engine model.	106
Figure 6-15. Boeing 767-200ER showing the jet fuel distribution at time of impact.....	106
Figure 6-16. Calculated impact on an exterior wall by a fuel-laden wing section.	107
Figure 6-17. Response of a tower subassembly model to engine impact.	108
Figure 6-18. Side view of simulated aircraft impact into WTC 1, Case B.	110
Figure 6-19. Column damage levels.	112
Figure 6-20. Case B damage to the slab of floor 96 of WTC 1.	112
Figure 6-21. Case B simulation of response of contents of 96 th floor of WTC 1.	113
Figure 6-22. Combined structural damage to the floors and columns of WTC 1, Case A.	114
Figure 6-23. Combined structural damage to the floors and columns of WTC 1, Case B.	114
Figure 6-24. Combined structural damage to the floors and columns of WTC 2, Case C.	115
Figure 6-25. Combined structural damage to the floors and columns of WTC 2, Case D.	115
Figure 6-26. Observed and Case A calculated damage to the north face of WTC 1.	117
Figure 6-27. Schematic of observed damage (top) and Case A calculated damage (lower) to the north face of WTC 1.	118
Figure 6-28. Schematic of observed damage (above) and Case C calculated damage (right) to the south face of WTC 2.	118
Figure 6-29. Ceiling tile system mounted on the shaking table.....	120
Figure 6-30. Eight floor model of WTC 1 prior to aircraft impact.....	122
Figure 6-31. Fire test of a single workstation.	123
Figure 6-32. Interior view of a three-workstation fire test.....	124
Figure 6-33. Rubblized workstations.....	124
Figure 6-34. Three-workstation fire test, 2 min after the start.....	125
Figure 6-35. Measured and predicted heat release rate from the burning of three office workstations.	125
Figure 6-36. Upper layer temperatures on the 94 th floor of WTC 1, 15 min after impact.	127
Figure 6-37. Direction of simulated fire movement on floors 94 and 97 of WTC 1.	128
Figure 6-38. Predicted heat release rates for fires in WTC 1 and WTC 2.	130
Figure 6-39. Simple bar dimensions (in.).	134
Figure 6-40. Tubular column dimensions (in.).	134
Figure 6-41. Truss Dimensions (in.).	135
Figure 6-42. SFRM-coated steel components prior to a test.	135
Figure 6-43. Finite element representation of the insulated steel truss (blue), the SFRM (violet), and the ceiling (red).	136
Figure 6-44. Comparison of numerical simulations with measurements for the steel surface temperature at four locations on the top chord of a bare truss.	137

List of Figures

Figure 6-45. Comparison of numerical simulations with measurements for the temperature of the steel surface at four locations on the top chord of an insulated truss.....	137
Figure 6-46. Temperatures (°C) on the columns and trusses of the 96 th floor of WTC 1 at 6,000 s after aircraft impact, Case B.	139
Figure 6-47. Temperatures (°C) on the columns and trusses of the 81 st floor of WTC 2 at 3,000 s after aircraft impact, Case D.	139
Figure 6-48. Frames from animation of the thermal response of columns on the 96 th floor of WTC 1, Case A.	140
Figure 7-1. Simulated impact damage to 95 th floor of WTC 1, including stairwells, 0.7 s after impact.....	156
Figure 7-2. Simulated impact damage to WTC 2 on floor 78, 0.62 s after impact.....	156
Figure 7-3. Observations of building damage after initial awareness but before beginning evacuation in WTC 1.	161
Figure 7-4. Observations of building damage from tenant spaces in WTC 2.....	162
Figure 7-5. Location of the radio repeater.	165
Figure 7-6. Timing of FDNY unit arrivals.	166
Figure 7-7. Fire Command Board located in the lobby of WTC 1.	168

LIST OF TABLES

Table P-1.	Federal building and fire safety investigation of the WTC disaster.....	xxx
Table P-2.	Public meetings and briefings of the WTC Investigation.	xxxiii
Table E-1.	Topics of NIST recommendations for improved public safety in tall and high-risk buildings.....	xliv
Table 1-1.	Use of floors in the WTC towers.	5
Table 2-1.	Locations of occupants of WTC 1.	26
Table 3-1.	Tenants on impact floors in WTC 2.....	39
Table 3-2.	Location of occupants of WTC 2.....	42
Table 4-1.	Likely locations of WTC decedents at time of impact.....	48
Table 5-1.	Specified steel grades for various applications.....	67
Table 5-2.	Types and locations of SFRM on fire floors.....	74
Table 5-3.	Floors of focus.	78
Table 6-1.	Times for major events on September 11, 2001.....	84
Table 6-2.	Indications of major structural changes up to collapse initiation.....	87
Table 6-3.	Measured and calculated natural vibration periods (s) for WTC 1.....	93
Table 6-4.	Summary of aircraft impact conditions.....	108
Table 6-5.	Input parameters for global impact analyses.....	109
Table 6-6.	Values of WTC fire simulation variables.....	126
Table 6-7.	Summary of insulation on steel components.	136
Table 6-8.	Regions in WTC 1 in which temperatures of structural steel exceeded 600 °C.	141
Table 6-9.	Regions in WTC 2 in which temperatures of structural steel exceeded 600 °C.	141
Table 6-10.	Comparison of global structural model predictions and observations for WTC 1, Case B.	153
Table 6-11.	Comparison of global structural model predictions and observations for WTC 2, Case D.....	153

This page intentionally left blank.

LIST OF ACRONYMS AND ABBREVIATIONS

Acronyms

AA	American Airlines
ARA	Application Research Associates
ASTM	ASTM International
BOCA	Building Officials and Code Administrators
BPS	Building Performance Study
FCD	Fire Command Desk
FDNY	The Fire Department of the City of New York
FDS	Fire Dynamics Simulator
FEMA	Federal Emergency Management Agency
FSI	Fire Structure Interface
IBC	International Building Code
LERA	Leslie E. Robertson Associates
NFPA	National Fire Protection Association
NIST	National Institute of Standards and Technology
NYC	New York City
NYPD	New York City Police Department
NYS	New York State
PANYNJ	The Port Authority of New York and New Jersey
PAPD	Port Authority Police Department
SFRM	sprayed fire-resistive material
SGH	Simpson Gumpertz & Heger, Inc.
SOM	Skidmore, Owings and Merrill
UA	United Airlines
USC	United States Code
WSHJ	Worthington, Skilling, Helle and Jackson
WTC	World Trade Center
WTC 1	World Trade Center 1 (North Tower)

WTC 2 World Trade Center 2 (South Tower)

WTC 7 World Trade Center 7

Abbreviations and Conversion Factors

°C	degrees Celsius	$T (^{\circ}\text{C}) = 5/9 [T (^{\circ}\text{F}) - 32]$
°F	degrees Fahrenheit	
ft	feet	
gal	gallon	$1 \text{ gal} = 3.78 \times 10^{-3} \text{ m}^3$
GJ	gigajoule	
GW	gigawatt	
in.	inch	
kg	kilogram	
kip	1,000 lb	
ksi	1,000 lb/in. ²	
lb	pound	$1 \text{ lb} = 0.453 \text{ kg}$
m	meter	$1 \text{ m} = 3.28 \text{ ft}$
μm	micrometer	
min	minute	
MJ	megajoule	
MW	megawatt	
psi	pounds per square inch	
s	second	
T	temperature	

PREFACE

Genesis of This Investigation

Immediately following the terrorist attack on the World Trade Center (WTC) on September 11, 2001, the Federal Emergency Management Agency (FEMA) and the American Society of Civil Engineers began planning a building performance study of the disaster. The week of October 7, as soon as the rescue and search efforts ceased, the Building Performance Study Team went to the site and began its assessment. This was to be a brief effort, as the study team consisted of experts who largely volunteered their time away from their other professional commitments. The Building Performance Study Team issued its report in May 2002, fulfilling its goal “to determine probable failure mechanisms and to identify areas of future investigation that could lead to practical measures for improving the damage resistance of buildings against such unforeseen events.”

On August 21, 2002, with funding from the U.S. Congress through FEMA, the National Institute of Standards and Technology (NIST) announced its building and fire safety investigation of the WTC disaster. On October 1, 2002, the National Construction Safety Team Act (Public Law 107-231), was signed into law. (A copy of the Public Law is included in Appendix A). The NIST WTC Investigation was conducted under the authority of the National Construction Safety Team Act.

The goals of the investigation of the WTC disaster were:

- To investigate the building construction, the materials used, and the technical conditions that contributed to the outcome of the WTC disaster.
- To serve as the basis for:
 - Improvements in the way buildings are designed, constructed, maintained, and used;
 - Improved tools and guidance for industry and safety officials;
 - Recommended revisions to current codes, standards, and practices; and
 - Improved public safety.

The specific objectives were:

1. Determine why and how WTC 1 and WTC 2 collapsed following the initial impacts of the aircraft and why and how WTC 7 collapsed;
2. Determine why the injuries and fatalities were so high or low depending on location, including all technical aspects of fire protection, occupant behavior, evacuation, and emergency response;
3. Determine what procedures and practices were used in the design, construction, operation, and maintenance of WTC 1, 2, and 7; and
4. Identify, as specifically as possible, areas in current building and fire codes, standards, and practices that warrant revision.

NIST is a nonregulatory agency of the U.S. Department of Commerce's Technology Administration. The purpose of NIST investigations is to improve the safety and structural integrity of buildings in the United States, and the focus is on fact finding. NIST investigative teams are authorized to assess building performance and emergency response and evacuation procedures in the wake of any building failure that has resulted in substantial loss of life or that posed significant potential of substantial loss of life. NIST does not have the statutory authority to make findings of fault nor negligence by individuals or organizations. Further, no part of any report resulting from a NIST investigation into a building failure or from an investigation under the National Construction Safety Team Act may be used in any suit or action for damages arising out of any matter mentioned in such report (15 USC 281a, as amended by Public Law 107-231).

Organization of the Investigation

The National Construction Safety Team for this Investigation, appointed by the then NIST Director, Dr. Arden L. Bement, Jr., was led by Dr. S. Shyam Sunder. Dr. William L. Grosshandler served as Associate Lead Investigator, Mr. Stephen A. Cauffman served as Program Manager for Administration, and Mr. Harold E. Nelson served on the team as a private sector expert. The Investigation included eight interdependent projects whose leaders comprised the remainder of the team. A detailed description of each of these eight projects is available at <http://wtc.nist.gov>. The purpose of each project is summarized in Table P-1, and the key interdependencies among the projects are illustrated in Fig. P-1.

Table P-1. Federal building and fire safety investigation of the WTC disaster.

Technical Area and Project Leader	Project Purpose
Analysis of Building and Fire Codes and Practices; Project Leaders: Dr. H. S. Lew and Mr. Richard W. Bukowski	Document and analyze the code provisions, procedures, and practices used in the design, construction, operation, and maintenance of the structural, passive fire protection, and emergency access and evacuation systems of WTC 1, 2, and 7.
Baseline Structural Performance and Aircraft Impact Damage Analysis; Project Leader: Dr. Fahim H. Sadek	Analyze the baseline performance of WTC 1 and WTC 2 under design, service, and abnormal loads, and aircraft impact damage on the structural, fire protection, and egress systems.
Mechanical and Metallurgical Analysis of Structural Steel; Project Leader: Dr. Frank W. Gayle	Determine and analyze the mechanical and metallurgical properties and quality of steel, weldments, and connections from steel recovered from WTC 1, 2, and 7.
Investigation of Active Fire Protection Systems; Project Leader: Dr. David D. Evans; Dr. William Grosshandler	Investigate the performance of the active fire protection systems in WTC 1, 2, and 7 and their role in fire control, emergency response, and fate of occupants and responders.
Reconstruction of Thermal and Tenability Environment; Project Leader: Dr. Richard G. Gann	Reconstruct the time-evolving temperature, thermal environment, and smoke movement in WTC 1, 2, and 7 for use in evaluating the structural performance of the buildings and behavior and fate of occupants and responders.
Structural Fire Response and Collapse Analysis; Project Leaders: Dr. John L. Gross and Dr. Therese P. McAllister	Analyze the response of the WTC towers to fires with and without aircraft damage, the response of WTC 7 in fires, the performance of composite steel-trussed floor systems, and determine the most probable structural collapse sequence for WTC 1, 2, and 7.
Occupant Behavior, Egress, and Emergency Communications; Project Leader: Mr. Jason D. Averill	Analyze the behavior and fate of occupants and responders, both those who survived and those who did not, and the performance of the evacuation system.
Emergency Response Technologies and Guidelines; Project Leader: Mr. J. Randall Lawson	Document the activities of the emergency responders from the time of the terrorist attacks on WTC 1 and WTC 2 until the collapse of WTC 7, including practices followed and technologies used.

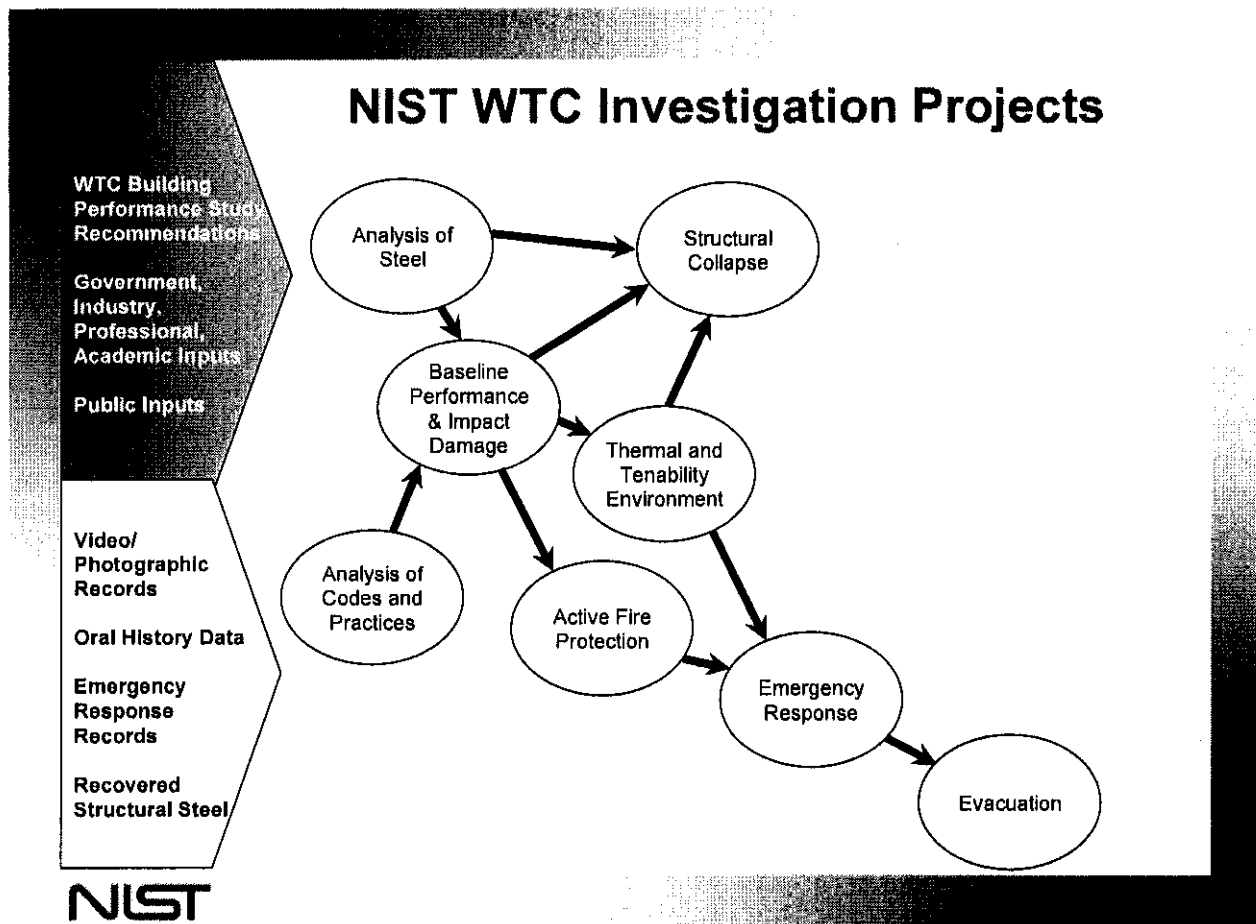


Figure P-1. The eight projects in the federal building and fire safety investigation of the WTC disaster.

National Construction Safety Team Advisory Committee

The NIST Director also established an advisory committee as mandated under the National Construction Safety Team Act. The initial members of the committee were appointed following a public solicitation. These were:

- Paul Fitzgerald, Executive Vice President (retired) FM Global, National Construction Safety Team Advisory Committee Chair
- John Barsom, President, Barsom Consulting, Ltd.
- John Bryan, Professor Emeritus, University of Maryland
- David Collins, President, The Preview Group, Inc.
- Glenn Corbett, Professor, John Jay College of Criminal Justice
- Philip DiNenno, President, Hughes Associates, Inc.